TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 800

TESTS ON STIFFENED CIRCULAR CYLINDERS

By Marshall Holt
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SUMMARY

Compressive tests were made of two series of stiffened circular cylindrical shells under axial load. All the shells were 16 inches in diameter by 24 inches in length and were made of aluminum-alloy sheet curved to the proper radius and welded with one longitudinal weld. The ratios of diameter to thickness of shell wall in the two series of specimens were 258 and 572. Strains were measured with Huggenberger tensometers at a number of gage lines on the stiffeners and shell. The test results are discussed in the light of published information on the subject.

The results of these tests indicate that a spacing of circumferential stiffeners equal to 0.67 times the radius is too great to strengthen the shell wall appreciably. The results are not inclusive enough to show the optimum in stiffener size and spacing for longitudinal stiffeners. Plain cylinders without stiffeners developed ultimate strengths approximately half as great as the buckling strengths computed by the equation resulting from the classical theory and slightly greater than those computed by Donnell's large deflection theory.

INTRODUCTION

In lightweight construction, especially in aircraft and marine structures, it is quite common to use a stiff framework covered by a thin metallic sheet. Under service loads the thin sheet and the frame act as a unit. The condition of the design may require either that the sheet retain its original curvature or degree of initial flatness or that the sheet be allowed to develop elastic wrinkles thus throwing most of the load onto the frame, or at least causing a redistribution of stress. Several articles in the literature give analyses of the action of seminonocoque structures under certain loading conditions. (See references 1 to 10.)

Inasmuch as a stiffened cylinder is statically indeterminate to a high degree under certain conditions, any analytical study should be checked by tests of representative structures using the loading conditions treated in the analysis. As part of a program of study of the strength and the stability of thin-sheet construction, tests were undertaken by the Aluminum Research Laboratories for the study of the distribution of stress in thin-wall structures. Stiffened flat sheet as well as stiffened circular cylinders were subjected to various loading conditions. The results of bending tests on stiffened flat sheet are discussed in reference 11.

SPECIMENS AND METHOD OF TEST

The specimens used in the tests discussed herein were stiffened cylindrical shells, 16 inches in diameter by 24 inches in length. The shells were formed of Alcoa alloy 53S-T sheet (Navy Dept. Specification 47A12a) curved to the proper radius and welded with one longitudinal weld. In one set of specimens, the wall thickness was 0.062 inch and, in a similar set, the wall thickness was 0.028 inch. The specimens are shown in the photographs of figures 1 and 2. The stiffeners were formed from Alcoa alloy 52S-1/2H sheet (Navy Dept. Specification 47A116) of the same thickness as the shell wall and attached by spot welding. The spots were spaced about 3/4 inch apart in the 0.062-inch shell and about 1/2 inch apart in the 0.028-inch shell. This close spacing was used to minimize the probability of failures by tearing the spots. The cross sections of the stiffeners and the section elements are shown in figure 3.

The tensile properties of the materials given in table I are in accord with the Specifications for these materials.

The specimens with stiffeners were subjected to test at a number of stages in their fabrication. For example, specimen G, shown in figure 1 with eight longitudinal stiffeners, was first tested with only four stiffeners spaced 90° apart. The second test was made after the next set of four stiffeners had been attached, reducing the spacing to 45° (6.28 in. = 0.785R). The schedule of tests for all the specimens is shown in table II and a description of the specimens is given in table III. A plain cylinder of each thickness of sheet was included for comparison.

In these tests the specimens were carefully centered in the testing machine, and measurements for strain were made at a number of points spaced 3 inches apart on several longitudinal elements of the shells and on the stiffeners. The end gage lines were $1\frac{1}{2}$ inches from the ends of the specimens. The gage lines were located by a combination of a compass direction (E or W) and a number. Thus, E6 is at the section $16\frac{1}{2}$ inches from the bottom on the element toward the east as the specimen was placed in the testing machine.

While the specimens were being placed in the testing machine, they were held circular by tight-fitting forms with circular holes of proper diameter accurately machined in them. These forms were located at the extreme ends of the specimen and clamped to the heads of the testing machine, as shown in figure 4. They were removed after a small load had been applied to the specimen.

The strains were measured with Huggenberger tensometers using a gage length of 1 inch. Measurements were made for over-all shortening of the specimen with dial gages at the four corners of the bearing plates. In all the tests, readings were taken at a series of loads so that relations between the load and the stress or deflection could be determined. In the final test the specimens were loaded to destruction.

The tests were made in an Amsler testing machine of 300,000-pound maximum capacity using an intermediate load range. In the case of the specimens with 0.028-inch wall, the heads were equipped with ball-bearing spherical seats that have a known low resistance to tipping and turning. Because the capacity of these heads was relatively low, they could not be used in the tests on the specimens with 0.062-inch wall; a bearing with a plain spherical seat was therefore used at one end and a bearing fixed against tipping and turning was used at the other end.

Care was taken in all except the final test to avoid overstressing the specimen and thus spoiling it for use in the subsequent tests with additional stiffeners.

The ends of the specimens were carefully machined flat, mutually parallel, and perpendicular to the axis of the cylinder by turning the specimens on a special expansion arbor in a lathe.

RESULTS AND DISCUSSION

Because of the very large amount of extensometer data taken in these tests, only a few of the load-stress curves from specimen P are given. These are considered typical of the data for all the specimens.

The load-stress curves for gage lines on two diametrically opposite elements of specimen P with eight stiffeners are shown in figure 5. Two straight lines are shown with the data for each gage line. The solid line has been drawn to represent the data and the dash line has been drawn to represent the average computed stress (P/A) using the same origin as the solid line. In general, the agreement between the two lines is very good, the maximum variation for the load of 14,000 pounds being 900 pounds per square inch, or about 11 percent.

At the inception of this investigation it was thought that buckling of the shell wall could be detected by a departure of the load-strain curves from a straight line and that with such a close spacing of the gage lines the load-strain curves would depart in alternate directions. In other words, it was thought that the gage lines were spaced closely enough together so that alternate ones would be on the concave and the convex sides of the longitudinal element after the shell wall buckled. Thus, the measured stress on one gage line would increase faster than the average and the measured stress on the next would increase less rapidly than the average. It is quite apparent that no indication of buckling of the cylinders is given by these load-measured stress curves. In view of the sudden failures that will be discussed later, it is possible that this method of testing is not satisfactory for determining the critical buckling load; that is, for a specimen of these proportions the critical buckling load and the ultimate load may be the same value.

The specimens after failure are shown in figures 1 and 2. All the cylinders with stiffeners failed suddenly. In most cases collapse was accompanied by a loud report.

In the case of specimens F and N, which had no stiffeners, failure was preceded by the formation and growth of a buckle in or adjacent to the longitudinal weld. Since the longitudinal elements containing the welds were not exactly straight, such a failure is not surprising. The failure of specimen K (fig. 1) is rather interesting in that no diamond-shape buckles were formed but only a circular bulge at the middle stiffener.

From a comparison of the size of the buckles in the various specimens, it appears that the spacings of the stiffeners were not such as to change materially the size of the wave; the natural wave pattern, however, is slightly changed in some cases. Since the buckle pattern is not changed very much by the stiffeners, only a little increase in the critical buckling stress of the shell wall would be expected. In other words, the portions of the shell wall between the stiffeners could deform into buckles of the same size and at about the same unit stress as though there were no stiffeners at all.

The maximum compressive loads supported by the specimens and the average stresses based on the total cross-sectional area are shown in table IV. The ultimate strengths of the cylinders with 0.062-inch walls are greater than the proportional limit of the material in the stiffeners but less than that of the material in the shell wall. The ultimate strengths of the cylinders with 0.028-inch walls are all in the range of elastic stresses. A comparison of the unit stresses at failure of the stiffened and unstiffened cylinders indicates that the longitudinal stiffeners alone brought about an increase in strength (P/A stress) from 17 to 27 percent over the unstiffened cylinder. The effectiveness of the circumferential stiffeners is not definite. In the case of the cylinders with 0.062-inch walls, the circumferential stiffeners alone produced an increase in strength from 5 to 15 percent over the strength of the unstiffened cylinder and, when used in conjunction with the longitudinal stiffeners, there was no increase in strength over that of the cylinders with only longitudinal stiffeners. In the case of the cylinders with 0.028-inch walls the reverse is true; the circumferential stiffeners alone produced no benefit but, in conjunction with the longitudinal stiffeners, there was an increase in strength from 12 to 19 percent over that for the longitudinal stiffeners alone. Comparisons of the load-weight ratios (maximum load divided by the weight of the specimen) give this same confused picture of the benefit of circular stiffeners. Undoubtedly, the relative proportions of the cylinders and the stiffeners are factors influencing this comparison.

In reference 9 it is stated "If the 'coefficient' $d/r > 350$, the load can be resisted by the plating alone and the stringers discarded (and put into the plating)." The term d signifies the compressive load in pounds per inch of perimeter and r is the radius of the cylinder in inches. The foregoing condition can be transformed by considering the total load P instead of the unit load d; then it becomes

$$P > 350\ (2\pi r^2)$$

or

$$P > 2200\ r^2$$

For these cylinders with a radius of 8 inches the limiting value of P is 141,000 pounds. This value indicates that, according to reference 9, these specimens would be expected to be stronger with stiffeners (as-built) than similar unstiffened cylinders of the same radius and weight (increased wall thickness).

This statement will be investigated in the following manner. The equation of the theoretically correct form for buckling strengths of circular cylinders is:

$$\frac{P}{A} = KE\,\frac{t}{r} \qquad (1)$$

in which

- P/A average compressive stress at buckling of shell wall, pounds per square inch
- K coefficient depending on the accuracy of fabricating cylinders and on testing technique
- E modulus of elasticity, pounds per square inch
- t thickness of shell wall, inches
- r radius of curvature of the shell wall, inches

The curve shown in figure 6 was drawn in accordance with this equation with K chosen to approximate the test results from specimens F and N. The value of K for this curve was found to be 0.3. Now, an unstiffened cylinder of the same material and with the same radius and weight as specimen H would have a wall thickness equal to 0.0975 inch and a ratio of radius to wall thickness equal to 82. The cross-sectional areas would be the same and the corresponding maximum load on the unstiffened cylinder would be about 156,000 pounds. From this result it appears that a plain cylinder stronger than specimen H could be made by increasing the wall thickness by an amount such that the weights of the two specimens were equal. This is contrary to the conclusion quoted from reference 9.

Since the stiffeners on specimen H are relatively heavy, it may be possible to make a stronger specimen by using twice as many stiffeners, each one-half the size of those on specimen H. Whether the strength of such a specimen would exceed 156,000 pounds could be determined only by a test on such a specimen. This same logic applied to specimen Q indicates that a plain cylinder of the same weight would have an ultimate strength of about 27,600 pounds. This value represents an increase of about 12 percent over the strength of specimen Q. The general rule quoted from reference 9 is not in agreement with these test results. It seems quite apparent that greater strengths could be obtained if the material in the circumferential stiffeners were redistributed so as to make the wall thicker.

The greatest load-weight ratios were obtained from the cylinders with only longitudinal stiffeners, but it appears that even higher ratios could be obtained by redistributing the material in the stiffeners. For maximum strength-weight ratios, these few test results do not answer the question as to whether the material in the stiffeners can best be used in a larger number of smaller stiffeners or in increasing the wall thickness.

Reference 4 describes tests on specimens made of curved sheets with ratios of radius of curvature to thickness of sheet (r/t) ranging from 430 to 4060. In the discussion of the test results it is pointed out that the specimens with small values of r/t failed suddenly with practically no indication of elastic buckling, just as did the specimens described in this report. The specimens with the larger values of r/t indicated elastic buckling and values of effective width of sheet were determined. The following equation is given for determining the critical buckling stress:

$$\sigma_{cr} = 5E\left(\frac{t}{w}\right)^2 + 0.3E\left(\frac{t}{r}\right) \tag{2}$$

in which

σ_{cr} critical buckling stress, pounds per square inch

w width of panel between longitudinal stiffeners

Equation (2) for critical stress is a combination of equation (1) for unstiffened cylinders and a term involving the spacing of longitudinal stiffeners.* For the case of a cylinder with n longitudinal stiffeners each of the width kr,

$$w = \frac{2\pi r}{n} - kr \tag{3}$$

The equation for critical stress can be written as:

$$\sigma_{cr} = 5E\left(\frac{nt}{2\pi r - nkr}\right)^2 + 0.3E\,\frac{t}{r} \tag{2a}$$

$$= 0.3E\,\frac{t}{r}\left[1 + 16.67\left(\frac{n}{2\pi - nk}\right)^2 \frac{t}{r}\right] \tag{2b}$$

It can be seen from equation (2b) that the increase in critical stress which might be expected from the stiffeners is a function of the ratio of the wall thickness to the radius and of the number of stiffeners, that is, the spacing. In the case of the cylinders with 0.028-inch walls and eight stiffeners this equation reduces to

$$\sigma_{cr} = 0.3E\,\frac{t}{r}\,(1.134) \tag{2c}$$

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*The use of the value of 0.3 for K in equation (1) and the appearance of the term 0.3 t/r in equation (2) is a coincidence resulting from the fact that many investigators have found that this value represents the strength of unstiffened cylinders as determined by the careful testing of well-fabricated specimens.

Thus, one should expect the buckling strength of specimens P and Q to be about 13 percent greater than that of specimen N. The ultimate strengths of specimens P and Q, which may or may not be a good indication of the buckling strengths for specimens of these proportions, are 18 and 21 percent greater than that of specimen N.

The curve giving the strengths of unstiffened cylinders as shown in figure 6 and approximating the test results from specimens F and N is just about one-half as high as the curve obtained from the classical buckling theory of thin cylinders. This theory is represented by the equation for critical buckling stress (see reference 12):

$$\sigma_{cr} = \frac{Et}{r}\sqrt{\frac{1}{3(1-\mu^2)}} = 0.612\,\frac{Et}{r} \tag{4}$$

where μ is Poisson's ratio, taken as 1/3, and the other terms have been previously defined.

The large-deflection theory for the buckling strength of thin cylinders developed by L. H. Donnell in reference 13 leads to the equation

$$\sigma_{cr} = \frac{0.6\,\frac{t}{r} - 10^{-7}\,\frac{r}{t}}{1 + 0.004\,\frac{E}{Y}} \tag{5}$$

where Y is the yield strength of the material in pounds per square inch.

The strengths of specimens F and N are computed by equation (5) to be 21,400 and 9,500 pounds per square inch, respectively. The strengths developed in the tests are 22,140 and 10,830 pounds per square inch or 3 and 15 percent greater than computed values.

CONCLUSIONS

From the test data and discussion presented in this report, the following conclusions have been drawn:

1. The spacing of the circumferential stiffeners (0.67 times radius) was too great to obtain any appreciable strengthening of the shell wall when subjected to axial compressive loads.

2. Although the specimens with longitudinal stiffeners developed a greater compressive strength than the similar unstiffened shells, a consideration of the relation between the strength and the proportions of the shell indicates that a still greater strength could be obtained by redistributing the material in the stiffeners so as to increase the thickness of the shell wall. It is not possible to determine the optimum stiffener size and spacing from these few tests.

3. There was no indication of buckling of the shell wall prior to collapse of the stiffened specimens under axial compressive load.

4. The compressive strengths of the two unstiffened cylinders were just about half as great as those predicted by the classical buckling theory of cylinders. In other words, it appears that the strength of well-made and carefully tested thin-wall cylinders may be calculated by the formula

$$\sigma_{cr} = 0.3E \frac{t}{r}$$

where

E modulus of elasticity, pounds per square inch

t thickness of shell wall, inches

r radius of cylinder, inches

5. The large-deflection theory given by Donnell gives computed strengths slightly lower than these test results.

Aluminum Research Laboratories,
Aluminum Company of America,
New Kensington, Pa., December 4, 1940.

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TABLE I. TENSILE PROPERTIES OF MATERIALS USED IN STIFFENED CYLINDERS

Standard half-inch wide tensile specimen used[a]

Stress-strain relations determined with:

2-inch Martens extensometer on 0.028-inch sheet; 2-inch Ewing extensometer on 0.062-inch sheet

Material	Alloy	Thickness (in.)	With grain, W or across grain, X	Tensile strength (lb/sq in.)	Yield strength (offset 0.2 percent) (lb/sq in.)	Proportional limit[b] (lb/sq in.)	Elongation in 2 inches (percent)
Shell of specimens F to M	[c]53S-T	0.062	W	39,560	35,300	28,000	13.0
			X	39,440	34,500	28,000	12.0
Stiffeners of specimens F to M	[d]52S-1/2H	.062	X	36,990	28,600	18,000	12.0
Shell of specimens N to U	[c]53S-T	.0273	W	38,250	34,500	22,000	10.5
			X	38,180	33,900	22,000	10.0
Stiffeners of specimens N to U	[d]52S-1/2H	.0272	X	36,900	28,200	20,000	10.0

[a]Standard tension-test specimens for sheet metals as shown by figure 2 of "Tentative Methods of Tension Testing of Metallic Materials (E8-40T)," Supp. to A.S.T.M. Standards, Part I, 1940.

[b]Determined by method explained by L. B. Tuckerman in discussion of R. L. Templin's paper on "The Determination and Significance of the Proportional Limit in the Testing of Metals," Proceedings A.S.T.M., Part II, 1929.

[c]Nominal composition: 0.7 percent Si, 1.3 percent Mg, 0.25 percent Cr, remainder Al. Navy Dept. Specification 47A12a.

Nominal composition: 2.5 percent Mg, 0.25 percent Cr, remainder Al. Navy Dept. Specification 47A11b.

TABLE II. SCHEDULE OF TESTS ON STIFFENED CYLINDERS

(Tests made at various stages of completion)

Specimen	First test	Second test	Third test
F	No stiffeners	--------	--------
G and H	4 longitudinal stiffeners	8 longitudinal stiffeners	--------
J and K	1 circumferential stiffener	3 circumferential stiffeners	5 circumferential stiffeners
L and M	1 circumferential and 4 longitudinal stiffeners	3 circumferential and 4 longitudinal stiffeners	5 circumferential and 8 longitudinal stiffeners
N	No stiffeners	--------	--------
P and Q	4 longitudinal stiffeners	8 longitudinal stiffeners	--------
R and S	1 circumferential stiffener	3 circumferential stiffeners	5 circumferential stiffeners
T and U	1 circumferential and 4 longitudinal stiffeners	3 circumferential and 4 longitudinal stiffeners	5 circumferential and 8 longitudinal stiffeners

TABLE III. DESCRIPTION OF STIFFENED CYLINDERS

(Outside diameter of shell, 16 in.; length, 24 in.)

Specimen	Thickness of shell wall, t (in.)	First test		Second test		Third test	
		Weight (lb)	Cross-sectional area (sq in.)	Weight (lb)	Cross-sectional area (sq in.)	Weight (lb)	Cross-sectional area (sq in.)
F	0.0615	7.325	3.153	----	-------	----	-------
G	.0620	9.448	4.058	11.61	5.000	----	-------
H	.0615	9.412	4.054	11.55	4.985	----	-------
J	.0620	8.505	3.150	11.06	3.150	13.61	3.150
K	.0618	8.410	3.150	10.64	3.150	12.84	3.150
L	.0617	10.520	4.056	12.72	4.056	17.03	4.997
M	.0620	10.435	4.056	12.99	4.056	17.62	4.997
N	.0279	3.322	1.431	-----	-----	-----	-----
P	.0285	3.978	1.716	4.535	1.958	-----	-----
Q	.0280	3.922	1.689	4.480	1.932	-----	-----
R	.0285	3.717	1.425	4.340	1.425	4.925	1.425
S	.0285	3.698	1.425	4.280	1.425	4.900	1.425
T	.0277	4.169	1.702	4.760	1.702	5.955	1.945
U	.0285	4.250	1.702	4.862	1.702	6.010	1.945

TABLE IV. RESULTS OF COMPRESSIVE TESTS ON

STIFFENED CYLINDERS

(Load applied axially)

1	2	3	4	5	6	7
Specimen	Length (in.)	Thickness (in.)	Weight (lb)	Area, A (sq in.)	Maximum load, P (lb)	Ultimate strength, P/A (lb/sq in.)
Thickness of shell walls, 0.062 inch						
F	23-31/32	0.0615	7.33	3.153	69,800	22,140
G	23-15/16	.0620	11.61	5.000	129,800	25,960
H	23-7/8	.0615	11.55	4.985	139,200	28,000
J	23-13/16	.0620	13.61	3.150	80,100	25,460
K	23-7/8	.0618	12.84	3.150	73,200	23,200
L	23-3/4	.0617	17.03	4.997	132,500	26,600
M	23-27/32	.0620	17.62	4.997	130,000	26,000
Thickness of shell wall, 0.028 inch						
N	23-31/32	0.0279	3.32	1.431	15,500	10,830
P	23-7/8	.0285	4.54	1.958	25,750	13,150
Q	23-29/32	.0280	4.48	1.932	24,675	12,770
R	23-13/16	.0285	4.93	1.425	14,950	10,450
S	23-13/16	.0285	4.90	1.425	13,850	9,700
T	23-7/8	.0277	5.96	1.945	28,600	14,700
U	23-7/8	.0285	6.01	1.945	29,600	15,200

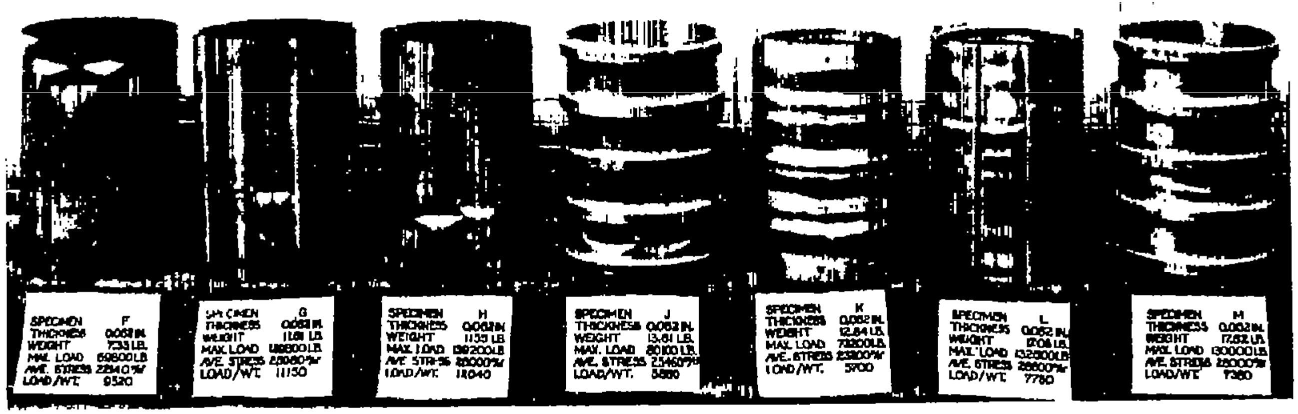


Figure 1.- Stiffened cylinders after failure under compressive load. Length of specimens, 24 inches; diameter of shell, 16 inches; thickness of shell wall, 0.062 inch.

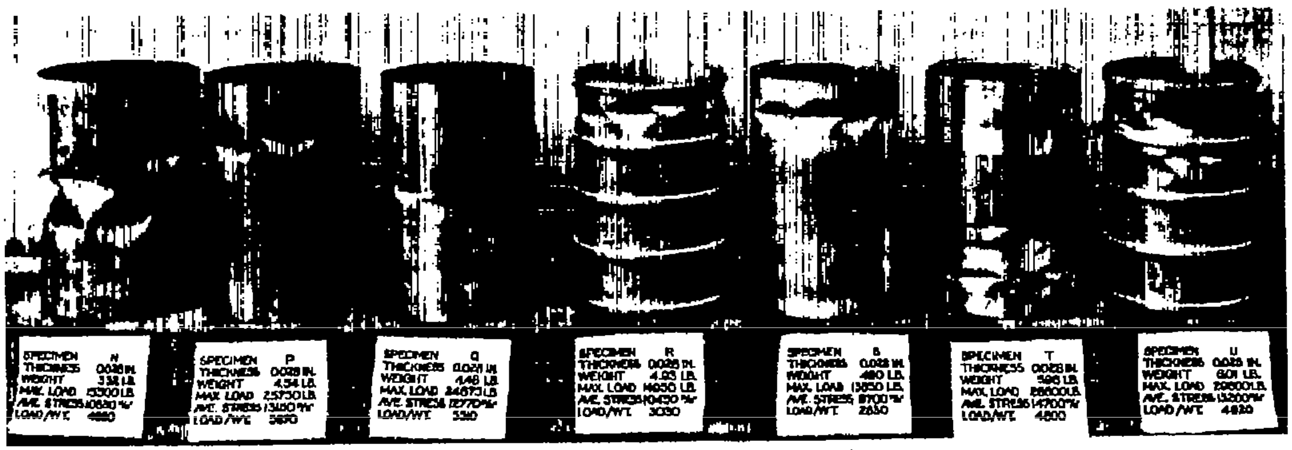
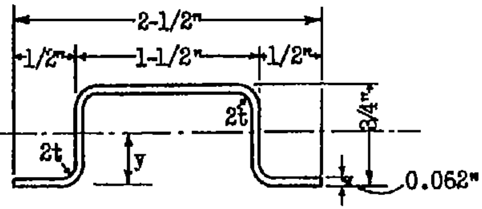


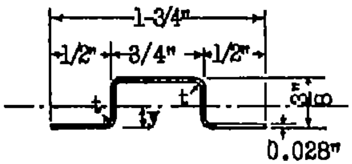
Figure 2.- Stiffened cylinders after failure under compressive load. Length of specimens, 24 inches; diameter of shell, 16 inches; thickness of shell wall, 0.028 inch.

Stiffener C1



	Nominal	Measured
Area, sq in.	0.246	0.247
Weight, lb /ft	0.284	0.286
y, in.	0.418	0.426
I_{xx}, in.^{4}	0.023	0.020

Stiffener D



	Nominal	Measured
Area, sq in.	0.070	0.060
Weight, lb /ft	0.080	0.072
y, in.	0.170	---
I_{xx}, in.^{4}	0.0017	0.00113

FIGURE 3.-

DIMENSIONS AND SECTION ELEMENTS OF STIFFENERS.

Stiffeners Formed from Sheet.

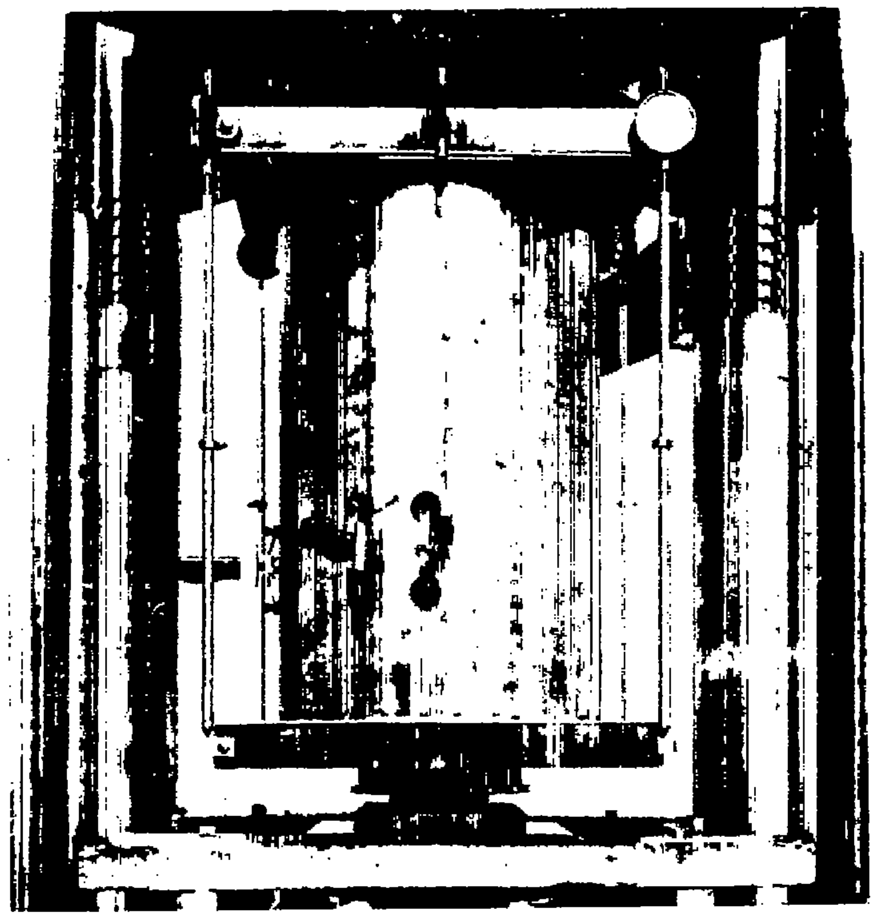
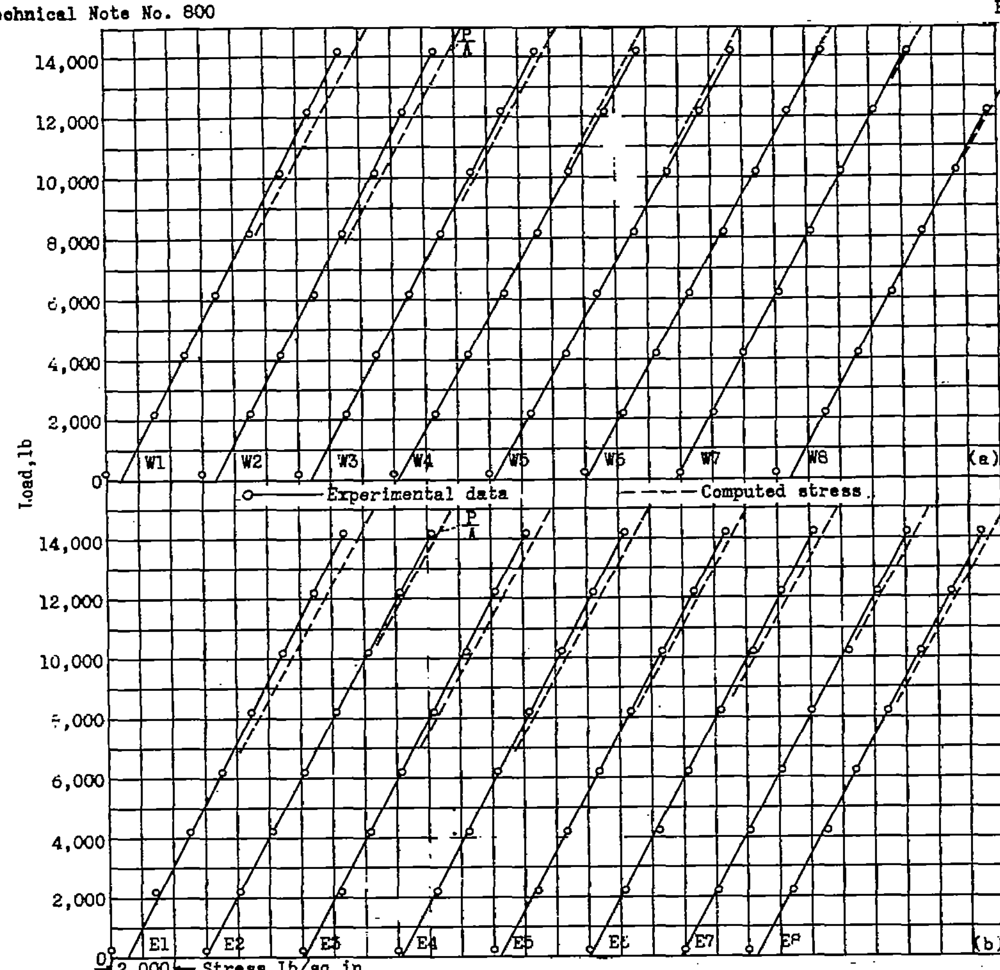


Figure 4.- Setup for test with axial compressive load on stiffened cylinder. (Heads with ball-bearing spherical seats shown).



(a)West gage lines. (b)East gage lines.

Figure 5.- Load-stress curves of compression test on stiffened cylinder P, 53S-T shell with light 52S-1/2H longitudinal stiffeners.

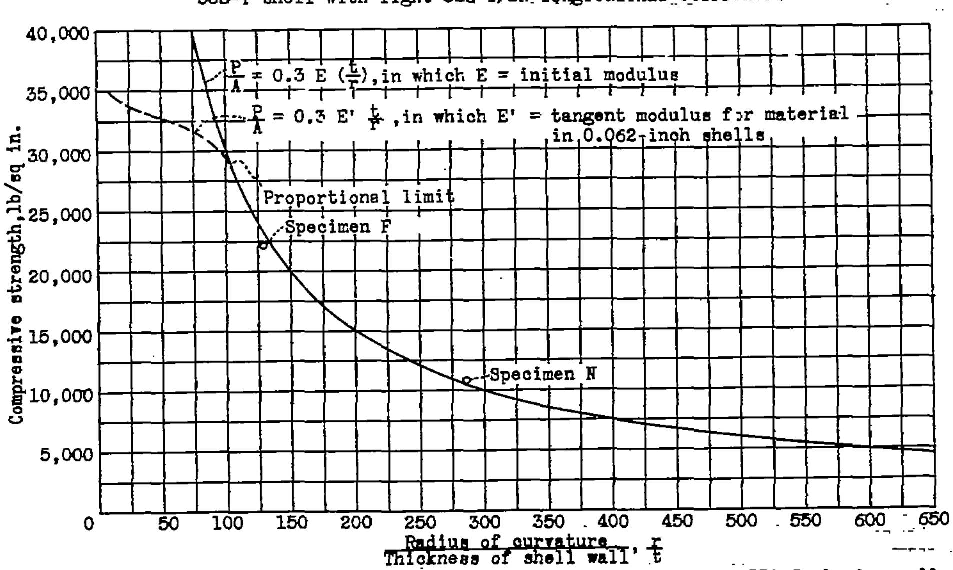


Figure 6.- Compressive strength of unstiffened cylinders of 53S-T aluminum alloy.